REMARKS

Claims 1, 3, 5-9, 11, 12 and 25-34 are pending in this application. Claims 2, 4, 8, 10, and 12-24 are canceled.

It is noted that the claim amendments, if any, are made only for more particularly pointing out the invention, and not for distinguishing the invention over the prior art, narrowing the claims or for any statutory requirements of patentability. Further, Applicants specifically state that no amendment to any claim herein should be construed as a disclaimer of any interest in or right to an equivalent of any element or feature of the amended claim.

With respect to the prior art rejections, claims 1-3, 5-9, 11, 12 and 25-32 stand rejected under 35 U.S.C. § 103(a) as unpatentable over Ota, et al. (JP 04-085972), further in view of Fujimoto, et al. (U.S. Patent No. 6,242,761).

This rejection is again respectfully traversed in the following discussion.

I. THE CLAIMED INVENTION

The invention, as described in independent claim 1 for example, is directed to an electrode for a p-type SiC that includes a first electrode material, and a second electrode material of aluminum (Al). The first and second electrode materials exhibit a eutectic reaction at a temperature of 600°C or lower and a layer made of the first electrode material is in contact with a surface of the p-type SiC (Application at page 3, lines 1-4; page 5, lines 17-21). The first electrode material comprises germanium (Ge).

This structure is important because the formation of the first electrode material having such eutectic characteristics accelerates the eutectic reaction at lower temperatures and provides a better ohmic junction (Application at page 3, lines 5-12; page 4, lines 20-23).

Conventional SiC electrodes, as described in the Background of the present Application, use a combination of titanium (Ti) and aluminum (Al) in an effort to produce an ohmic electrode. However, such conventional SiC electrodes contain a large amount of Al to reduce resistance and need to be heat treated at temperatures of about 1000°C . As a result of these high temperatures devices using such electrodes have reduced functionality and a decreased useful lifecycle caused by deterioration of surface morphology and thermal

damage during heat treatment (Application at page 1, line 23-page 2, line 15).

In contrast, in an exemplary embodiment, this invention may provide an electrode for a p-type SiC having a good surface homology and little thermal damage to the semiconductor crystal layers caused by the formation of the electrode (Application at page 2, lines 18-22).

II. THE PRIOR ART REJECTION

The Examiner continues to reject claims 1-3, 5-9, 11, 12, and 25-34 as obvious over JP 04-085972 to Ota et al., further in view of US Patent No. 6,242,761 to Fujimoto et al., based on the holding of *KSR*.

In an attempt to expedite prosecution, Applicants have decided to incorporate claim 2 into claim 1. Additionally, to demonstrate that the claimed invention was not known in the art, that the elements were not considered as substitutes at the time of the invention, and that unexpected results do indeed occur with the claimed invention, meaning that those of skill in the art were not aware of the benefits of the invention, Applicants submit a paper published after filing of the present application and including as authors several of the present inventors.

This publication, "Electrical properties and microstructure of ternary Ge/Ti/Al ohmic contacts to *p*-type 4H-SiC", clearly describes how the claimed invention was indeed novel in several aspects.

First, as clearly described in the second column of the first page (i.e., page 4976), at best, the conventional wisdom at the time of the invention would have been to use Ni in order to reduce annealing temperature of the binary Ti/Al ohmic contacts.

As further described in that paragraph and further demonstrated in Table II, the present inventors discovered that a thin layer of germanium (Ge) is even better than using Ni for decreases the annealing temperature in the environment of SiC. None of the cited references provide a suggestion that Ge would provide an improvement to the binary Ti/Al contact system in the SiC environment.

Relative to the rejection currently of record, Applicants respectfully submit that this rejection fails to establish a *prima facie* rejection for obviousness, even under the loosened guidelines resultant from KSR. Indeed, Applicants submit that the rejection of record reflects exactly what the US Supreme Court stated in that holding should be avoided:

"A factfinder should be aware, of course, of the distortion caused by hindsight bias and must be cautious of arguments reliant upon ex post reasoning."(Page 17 of the opinion)

That is, in the rejection of record the Examiner concedes that primary reference Ota (at least) fails to teach or suggest "*... the first and second materials exhibiting an eutectic reaction at a temperature of 600 °C or less, the use of nickel instead of germanium as the first electrode material adnd the thicknesses stated.*"

The Examiner relies upon secondary reference Fujimoto to overcome these deficiencies of primary reference Ota, pointing to the description at lines 20-36 of column 7 of Fujimoto as allegedly at least suggesting the missing elements.

According to the Examiner: "*It would have been obvious to a person of ordinary skill in the art at the time of invention to use germanium instead of nickel and that these materials show eutectic reactions at temperatures of 600 °C or less to realize good contact resistance and easy wire bonding. Additionally, all the claimed elements were known in the prior art and one skilled in the [art] could have combined the elements as claimed by known methods with no change in their respective functions, and the combination would have yielded predictable results to one of ordinary skill in the art at the time of the invention.*"

In response, Applicants again point out that, as clearly stated on page 5 of the USPTO translation, what primary reference Ota <u>does</u> teach for its p-type SiC electrode 7 is to use Ni (0.2μm)/Ti (0.02μm)/Al (0.5μm), which is subsequently heated by inert gas at <u>900-1000</u> °C for 5-10 minutes.

In contrast, the present invention teaches using Ge (60 nm)/ Ti (80 nm)/ Al (360 nm), which permits an <u>eutectic</u> reaction at a relatively lower temperature of <u>600 °C or less</u>, as described at lines 23-25 on page 9.

There is no suggestion in Ota to replace Ni with Ge. Nor is there any suggestion to use a lower temperature of the claimed invention, given the use of Ge rather than Ni. Finally, there is no suggestion Ota that the thickness of materials deposited for this electrode will form the eutectic reaction. As described, for example, at Wikipedia.org, "eutectic reaction" is a term of art meaning that all constituents crystallize substantially simultaneously from the molten state and requires a predetermined mixture of such proportions that the melting point is as low as possible.

Indeed, Applicants submit that primary reference Ota, as evidenced by the description on page 5 of the USPTO translation, can only reasonably be described as clearly <u>teaching</u>

against the claimed invention.

The Examiner's reliance on lines 20-36 of column 7 of secondary reference Fujimoto is also misplaced. Applicants respectfully point out that these lines do not even mention "eutectic", does not suggest an annealing temperature in the environment of either Ota or the claimed invention, and does not suggest that Ge is a simple substitute for Ni, let alone being a substitute in the claimed environment. These (mis)characterizations of secondary reference Fujimoto are clearly demonstrating a "... *distortion caused by hindsight bias* ...." that the *KSR* holding clearly explicitly warns should be avoided by the factfinder. The Examiner continues to miss the point that the present invention is relative to the SiC environment, and such SiC environment is an element of the claimed invention.

Moreover, Applicants submit that the results of the claimed invention are indeed unexpected, as can be understood by the description at lines 16-23 of page 4 of the present application:

"*The first electrode material is not particularly limited if the first electrode material is a material reacting with Si and exhibiting an eutectic reaction with Al at a relatively low temperature. For example, germanium (Ge) or the like can be used as the first electrode material. Because the addition of the first electrode material accelerates the reaction at a low temperature, decrease in the contact-forming temperature can be attained.*"

Thus, contrary to the Examiner's implication, it was not known in the art at the time of the invention of the effect of Ge in the SiC environment, for the binary Ti/Al contact system. The description above clearly describes how Ge was discovered to be an accelerant at low temperature for the SiC environment for a contact using Al, based upon an eutectic composition ratio.

That is, as clearly described in the left column of the first page (e.g., page 4976) of the attached publication "Electrical properties .... to p-type 4H-SiC" by Tsukimoto et al., the technique of getting low contact resistance to *p*-type 6H-SiC required an annealing at temperatures higher than 1000 °C, as demonstrated by Crofton et al. in their 1993 publication.

In the right hand column on this first page is also described how Konishi was able to reduce resistance by adding a thin Ni layer to binary TiAl alloy contacts. Also on the first page, the abstract of this publication explains the discovery, described in the present application, that adding a small amount of Ge to binary Ti/Al reduced ohmnic contact formation temperature to about 500 °C.

Therefore, in contrast to the Examiner's position, it was certainly not known by either Crofton or Konishi to use Ge in binary TiAl alloy contacts in the SiC environment.

Moreover, contrary to the Examiner's position that Applicants have failed to articulate the criticality of the relative thicknesses in the Ge/Ti/Al ternary alloy, as defined in the claimed invention, Applicants point out that this appendix publication confirms that the relative ratios are indeed critical and that such relative ratios were not common in the art in the SiC environment. As clearly shown in Table I of this appendix publication, the composition is indeed critical to resistance. Furthermore, as shown in Figures 1 and 2, even annealing time is demonstrated in this supporting publication as being a factor in the resistance.

Finally, Applicants bring to the Examiner's attention that even the Examiner's paraphrasing of the wording of the holding in *KSR* requires that all elements of the claimed invention must have been known and that the functions remain the unchanged. The evaluation of record overlooks that Ge was not known as a substitute for Ni, let alone a substitute in the SiC environment (e.g., an element of the claimed invention has a functional aspect not previously recognized) and that Ge was not known to serve as an accelerant in this SiC environment for lower temperature formation.

The Examiner's reliance on lines 20-36 of column 7 of Fujimoto to provide evidence of these facts is clearly misplaced, since the SiC environment is not being described in this reference. Moreover, as clearly described in lines 31-36 of column 7, these lines do not in any way point to or even reasonably suggest the binary or ternary structure of Ge and Al, let alone an eutectic ternary structure, since this sentence provides a listing of 16 materials that could be used to provide an electrode system having anywhere from a single layer all the way through a "multi-layered layer", that can only mean as using all 16 materials.

Therefore, even discounting the element of the SiC environment, relative to the Examiner's position that Fujimoto describes using Ge as a substitute for Ni, Applicants submit that the cited description in this reference actually suggests 16! combinations that would have to be tested before arriving at the claimed invention. This number of potential combinations represents an unimaginably large task and can only be reasonably considered as requiring an undue experimentation to even arrive at the three components used in the claimed invention of the dependent claims, let alone ratios of composition needed for the eutectic reaction.

Thus, in view of an unbiased evaluation of the actual description in Ota and Fujimoto, Applicants submit that the claimed invention is clearly non-obvious over these two references.

Therefore, as Fujimoto does not relate to a p-type SiC, there is no suggestion in Fujimoto to modify Ota as proposed by the Examiner and no indication in Fujimoto that a eutectic reaction will occur in the p-type SiC environment which even primary reference Ota clearly describes as being an extremely difficult environment in which to obtain desirable ohmic properties.

Hence, turning to the clear language of the claims, in Ota, even if modified by Fujimoto, there is no teaching or suggestion of: "An electrode for a p-type SiC, comprising a first electrode material, and a second electrode material of aluminum (Al), said first and second electrode materials exhibiting an eutectic reaction at a temperature of 600°C or lower, wherein a layer made of said first electrode material is in contact with a surface of the p-type SiC, said first electrode material comprising germanium (Ge)", as required by independent claim 1. The remaining independent claims have similar limitations.

Because the combination of references fails to disclose or suggest all of the features recited in the rejected claim, reconsideration and withdrawal of the rejection is respectfully requested.

III. CONCLUSION

In view of the foregoing, Applicants submit that claims 1, 3, 5-9, 11, 12 and 25-34, all the claims presently pending in the application, are patentably distinct over the prior art of record and are in condition for allowance. The Examiner is respectfully requested to pass the above application to issue at the earliest possible time.

Should the Examiner find the application to be other than in condition for allowance, the Examiner is requested to contact the undersigned at the local telephone number listed below to discuss any other changes deemed necessary in a telephonic or personal interview.

The Commissioner is hereby authorized to charge any deficiency in fees or to credit any overpayment in fees to Attorney's Deposit Account No. 50-0481.

Respectfully Submitted,

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Electrical properties and microstructure of ternary Ge/Ti/Al ohmic contacts to *p*-type 4H–SiC

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The high-power SiC devices require ohmic contact materials, which are prepared by annealing at temperatures lower than 800 °C. Recently, we demonstrated in our previous paper [J. Appl. Phys. 95, 2187 (2004)] that an addition of a small amount of Ge to the conventional binary Ti/Al contacts reduced the ohmic contact formation temperature by about 500 °C, and this ternary contacts yielded a specific contact resistance of approximately 1×10^{-4} Ω cm^2 after annealing at a temperature as low as 600 °C. In this paper, the electrical properties and the microstructures of the Ge/Ti/Al contacts (where a slash "/" indicates the deposition sequence) were investigated by current-voltage measurements and transmission electron microscopy observations, respectively, in order to understand the ohmic contact formation mechanism. Ti_3SiC_2 compound layers (which were previously observed at the metal/SiC interface in the Ti/Al ohmic contacts after annealing at temperatures higher than 1000 °C) were observed to grow epitaxially on the SiC surface after annealing at temperatures as low as 600 °C. The Ti_3SiC_2 layers were believed to act as a *p*-type intermediate semiconductor layer, which played a key role to reduce the Schottky barrier height at the contacting metal/SiC interface. Further reduction of the contact resistances of the Ge/Ti/Al contacts would be achieved by increasing the coverage of the Ti_3SiC_2 layers on the SiC surface. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1797546]

I. INTRODUCTION

Silicon carbide (4H–SiC) is one of the most attractive compound semiconductors for the next generation high-power and communication electronic devices. The 4H–SiC has the excellent intrinsic properties such as a wide band gap (3.3 eV), a high thermal conductivity (5 W/cm °C), a high electric-field breakdown strength (3×10^6 V/cm), and a high saturation electron velocity (2.7×10^7 cm/s).[1–4] The development of low-resistance ohmic contacts ($<1\times10^{-5}$ Ω cm^2) to *p*-type SiC is required to realize the reliable high performance devices.[5,6]

Crofton *et al.*[7] found that the binary TiAl alloy contacts yielded a low contact resistance to *p*-type 6H–SiC after annealing at temperatures higher than 1000 °C. Then, extensive investigations for the improvement of the TiAl contacts and development of the other *p*-type ohmic contact materials have been carried out by various authors.[8–14] A technique to deposit the contact materials and subsequently anneal at an elevated temperature [which is called as the deposition and annealing (DA) technique] has been conventionally used to prepare ohmic contacts to GaAs and to the other related compound semiconductors.[15] This DA technique is also used to fabricate the ohmic contacts to *p*-type SiC. However, a high-temperature annealing (as high as 1000 °C) was required for the conventional TiAl contacts to enhance a chemical reaction between the contact materials and the SiC, because SiC has a high chemical stability. This high annealing temperature caused a rough ohmic contact surface and reduced the capacitance of the gate oxide layers, which are not desirable for the SiC devices. Thus, the reduction of the annealing temperature for the contact formation was mandatory.

Konishi *et al.*[16] succeeded the reduction of the annealing temperature of the Ti/Al ohmic contacts by adding a thin Ni layer (which had a high chemical reactivity with SiC at a temperature as low as 500 °C) to the Ti/Al contacts. The Ni/Ti/Al contacts provided an ohmic behavior at a temperature of about 800 °C. (Here, a slash "/" between the metals indicates the deposition sequence of the contacting materials.) Microstructures of the Ti/Al and the Ni/Ti/Al ohmic contacts were investigated by transmission electron microscopy (TEM) observations, and these contacts were found to grow Ti_3SiC_2 layers epitaxially on the SiC surface even though these ohmic contacts were fabricated at different annealing temperatures.[17] These results suggested that the Ni layer added to the conventional Ti/Al contacts enhanced the interfacial reactions at low temperatures. Recently, Sakai *et al.*[18] reported that an addition of a thin Ge layer to the Ti/Al contact had a stronger effect to reduce the ohmic contact formation temperature compared with that of the Ni addition to the Ti/Al contact. The Ge/Ti/Al ohmic contacts provided an ohmic behavior after annealing at temperature as low as 600 °C. They pointed out that a eutectic (liquid) Al–Ge (with a eutectic point of 420 °C) would facilitate the reaction between the contact materials and the SiC substrate at low temperatures. The Ge/Ti/Al ohmic contacts yielded the contact resistance of 1×10^{-4} Ω cm^2 after annealing at 600 °C. In order to apply these contact materials to various SiC devices, a further reduction of the ohmic contact materials is required.

The primary purpose of the present study is to understand the formation mechanism of the Ge/Ti/Al ohmic con-

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TABLE I. Layer structures and specific contact resistances of Ge/Ti/Al ohmic contacts.

Deposition sequence (nm)	Film thickness (nm)	Specific contact resistance (Ω cm^2)
Ge(24)/Ti(32)/Al(144)	200	1.03×10^{-4}
Ge(30)/Ti(40)/Al(180)	250	1.26×10^{-4}
Ge(36)/Ti(48)/Al(216)	300	1.36×10^{-4}
Ge(60)/Ti(80)/Al(360)	500	4.07×10^{-4}

tacts in order to obtain a clue to reduce further the contact resistance. For this purpose, the electrical properties and the microstructure at the contact materials/SiC interfaces after an isothermal annealing at 600 °C for various times are correlated. A special attention was paid whether or not a current transport mechanism of the Ge/Ti/Al ohmic contact is the same with the other TiAl-based contacts such as the conventional Ti/Al and Ni/Ti/Al contacts. Finally, a possibility to reduce further the contact resistances of the Ge/Ti/Al contacts is discussed.

II. EXPERIMENTAL PROCEDURES

The *p*-type 4H–SiC epitaxial layers (5-μm thick) doped with Al at 4.5×10^{18} cm^{-3}, which were grown on *n*-type 4H–SiC wafers (manufactured by Cree Research, Inc.), were used as the substrates. The SiC substrates had an 8°-off Si-terminated (0001) surfaces inclined toward a $\langle 2\bar{1}\bar{1}0\rangle$ direction. After the substrate surface was cleaned using the so-called Radio Corporation of America technique,[19] a 10-nm-thick sacrificial oxide (SiO_x) layer was grown on the SiC epilayer substrate by dry oxidation at 1150 °C for 60 min. The substrates with circular electrode patterns were prepared using a photolithographic technique by removing the SiO_x layers. The substrates were cleaned by dipping in a 5% of diluted hydrofluoric acid solution and rinsing in deionized water prior to the deposition of contact materials. Ge, Ti, and Al layers with high purities were deposited sequentially on the SiC substrate in a high-vacuum chamber, where the base pressure was below 5×10^{-8} Torr. The vacuum pressure during the deposition was lower than 1×10^{-6} Torr. The Ge and Ti layers were evaporated using an electron beam, and the Al was evaporated by a resistance heater. After lifting off the photoresist, the Ge/Ti/Al ohmic contacts were prepared by annealing at 600 °C in an ultrahigh-vacuum chamber, where the vacuum pressure was below 1×10^{-9} Torr. The layer structures and the total thicknesses of the Ge/Ti/Al contact materials investigated in this study are given in Table I. (The specific resistances given in this table will be explained later.) The layer thicknesses were chosen to give the average composition of the Ge (10 at. %), Ti (15 at. %), and Al (75 at. %), and the total thicknesses of the Ge/Ti/Al contacts were aimed to be 200, 250, 300, and 500 nm, respectively, where the layer thicknesses were measured by a quartz oscillator during deposition. The reasons to choose this average composition was that Al–Ge (28 at. %) gives a eutectic point of 420 °C, and aluminum rich (more than 75 at. %) in TiAl contacts were found to be essential to yield low contact resistance.[20]

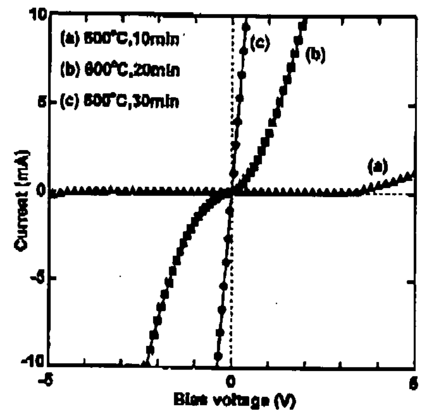

FIG. 1. Typical current-voltage (I–V) characteristics of a Ge(24 nm)/Ti(32 nm)/Al(144 nm) (200-nm-thick) contact after annealing at 600 °C for various times: (a) 10 min; ▲, (b) 20 min; ■, and (c) 30 min; ●.

The electrical properties (I–V characteristics) of the ohmic contacts were measured by a two-point probe method using circular patterns with an interspacing of 8 μm. The specific contact resistances were measured by a circular transfer length method using a four-point probe method, where multiple annular electrode patterns with interspacings of 4, 8, 16, 24, and 32 μm were used. The surface morphology of the contacts with the electrode patterns was observed using an optical microscope. The microstructural analysis at the ohmic contact metals/4H–SiC interfaces was performed using x-ray diffraction (XRD) and TEM. For an XRD analysis, RINT-2500 (Rigaku) with a Cu $K\alpha$ radiation operated at 30 kV and 100 mA was used. The interfacial structures and an orientation relationship between the ohmic contacts and the 4H–SiC substrates were characterized by the cross-sectional high-resolution TEM observations and selected area diffraction pattern (SADP) analysis, respectively, using a JEM-4000EX (JEOL) electron microscope operated at an accelerating voltage of 400 kV, equipped with a top-entry-type goniometer. The point-to-point resolution of this microscope was approximately 0.17 nm. Thin foil specimens for the present TEM observations were prepared by the standard procedures: cutting, gluing, mechanical grinding, dimple polishing, and Ar-ion sputter thinning.

III. EXPERIMENTAL RESULTS

A. Electrical properties of Ge/Ti/Al contacts

Figure 1 shows the typical I–V characteristics of the Ge/Ti/Al (200-nm-thick) contacts after annealing at 600 °C for various times. A nonohmic behavior is observed after annealing for 10 min [curve (a)]. However, the electrical property improves with increasing the annealing times [curve (b)], and the contact shows an ohmic behavior after annealing for 30 min, as seen in curve (c). Among the TiAl-based ohmic contacts, the Ge/Ti/Al contact is the only one contact material to provide an ohmic behavior after annealing at a temperature of 600 °C. The reduction of the annealing temperature to transit from a nonohmic behavior in the TiAl-

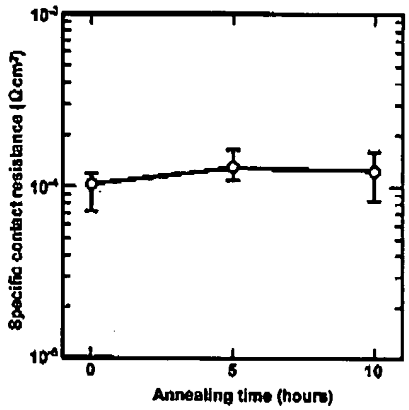

FIG. 2. Specific contact resistances (ρ_c) of the Ge/Ti/Al contacts before and after annealing isothermally at 400 °C for 5 and 10 h.

based contacts to the ohmic behavior is due to the addition of Ge, which is believed to enhance the chemical reactivity of Ti and Al with the SiC substrate at a low temperature by forming eutectic Al–Ge. The average specific contact resistances (ρ_c) of the Ge/Ti/Al ohmic contacts with various thicknesses after annealing at 600 °C for 30 min were summarized in the third column of Table I. The ρ_c values are found to decrease with decreasing the contact thicknesses, and the minimum ρ_c value of approximately $1 \times 10^{-4}\ \Omega\ \mathrm{cm}^2$ is obtained in the 200-nm-thick contact.

In order to investigate the thermal stability of the electrical properties during heat treatments at 400 °C, the Ge/Ti/Al contacts were isothermally annealed at 400 °C in an Ar atmosphere. Figure 2 shows the specific contact resistances of the 200-nm-thick contact before and after annealing at 400 °C for 5 and 10 h. The contact resistances do not change significantly after annealing for 10 h. This excellent thermal stability of the Ge/Ti/Al contacts is similar to that observed in the binary Ti/Al contacts by Tanimoto *et al.*[9]

B. Microstructures of Ge/Ti/Al ohmic contacts

1. Surface morphology

Smooth surface morphology is desirable for the contact materials to use in the manufacturing devices. Figure 3 shows an optical micrograph of the 200-nm-thick Ge/Ti/Al contact after annealing at 600 °C for 30 min. (The rough regions in the micrograph are the Ge/Ti/Al contact surface, and the band regions with circular gray contrast are the sacrificial oxide surface on the *p*-type SiC epilayer.) The edges of the contact electrodes are observed to be sharp and abrupt. As for the contact surface, the morphology is locally rough after annealing. However, the surface roughness was significantly improved compared with that of the binary Ti/Al contact.[12] The hillocks formed on the contact surface (which are indicated by the black arrows) are due to the formation of residual Al droplets, which did not react with the other elements. Using a stylus surface profiler, the maximum typical roughness was measured to be about 1 μm for the 500-nm-thick contact. The surface roughness was found to depend on the total thickness of the contact and decreased

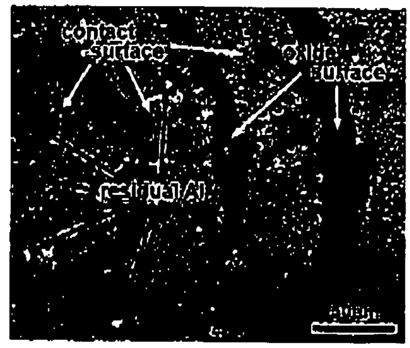

FIG. 3. Optical micrograph of the 200-nm-thick Ge/Ti/Al contact surface after annealing at 600 °C for 30 min.

with decreasing the contact thickness. Al metal exceeding 75 at.% in the Ge/Ti/Al contacts is believed to result in a formation of the rough surface, which is a characteristic of the TiAl-based ohmic contacts.

2. X-ray diffraction analysis

The XRD analysis was performed to characterize the microstructures of the Ge/Ti/Al ohmic contacts. Figures 4(a)–4(c) show the XRD profiles obtained from the Ge/Ti/Al (200-nm-thick) ohmic contacts annealed at 600 °C for 10, 20, or 30 min, which correspond to the $I-V$ characteristics shown in Figs. 1(a)–1(c), respectively. After annealing for 10 min, the binary Al_3Ti and Al_4C_3 compounds, which were formed by an interfacial chemical reaction, are detected by XRD analysis in addition to the unreacted Al and Ge [Fig. 4(a)]. Note that an amount of the Al_4C_3 compounds is quite small because the intensity of the peak diffracted from Al_4C_3 is very weak. As shown in Fig. 1(a), the $I-V$ characteristic did not show the ohmic behavior and the contact resistance is very high at the contact/SiC interface after annealing for 10 min. After annealing for an additional 10 min (20 min in total), the peaks corresponding to a ternary Ti_3SiC_2 compound are detected, as indicated by the solid square symbols in Fig. 4(b). At this stage, the con-

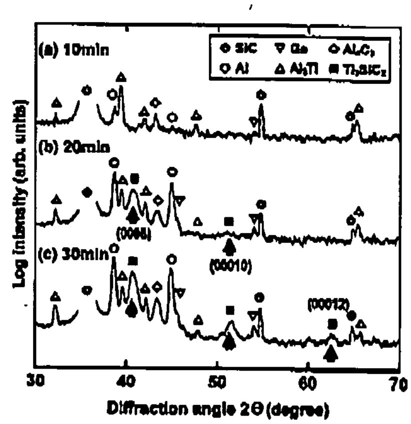

FIG. 4. XRD profiles of the 200-nm-thick Ge/Ti/Al contact after annealing at 600 °C for 10, 20, and 30 min.

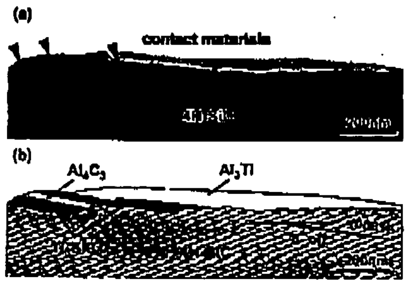

FIG. 5. (a) Cross-sectional bright-field TEM micrograph and (b) the corresponding schematic illustration of the 200-nm-thick Ge/Ti/Al contact formed on the 4H–SiC. (The incident electron beam is along the ⟨01$\bar{1}$0⟩ direction of 4H–SiC.)

tact resistance was reduced significantly compared with that annealed for 10 min, as shown in Fig. 1(b). After annealing for 30 min, it is observed that the Ti_3SiC_2 peak intensities increase, although the intensities of the peaks diffracted from the other compounds do not change significantly [Fig. 4(c)]. Only the Ti_3SiC_2 peaks diffracted from (000*l*) diffraction planes of a hexagonal structure are observed. This result indicates that the Ti_3SiC_2 layer has a strong (0001)-oriented texture on the SiC substrate. The microstructures observed in the Ge/Ti/Al ohmic contact are quite similar to those observed in the Ti/Al and Ni/Ti/Al ohmic contacts, which were annealed at 1000 and 800 °C, respectively.[17] Based on the present XRD results, the Ti_3SiC_2 layers formed in the Ge/Ti/Al ohmic contacts are believed to play an important role in the current transport through the metallic contact/SiC interface. In order to analyze the detailed microstructures in the Ge/Ti/Al contacts, the cross-sectional TEM observations were carried out and the results will be given in the next section.

3. Cross-sectional TEM observations

Interfacial microstructures at the interfaces between the Ge/Ti/Al ohmic contact and the 4H–SiC substrate were characterized by the cross-sectional TEM observation. Figures 5(a) and 5(b) show a cross-sectional bright-field TEM micrograph and the corresponding schematic illustration, respectively, of the Ge/Ti/Al (200-nm-thick) ohmic contact formed on the SiC substrate after annealing at 600 °C for 30 min. The incident electron beam is along the ⟨01$\bar{1}$0⟩ direction of the 4H–SiC substrate. The interface between the contact materials and the SiC substrate is observed to have a sawtooth-shaped facet structure. This unique morphology is typical in the TiAl-based ohmic contact on the epitaxial SiC layers, which are grown on the 8°-off (0001)-oriented SiC substrate. From the present TEM micrograph, the reaction depth in the SiC substrate is found to be shallow (~50 nm). The binary Al_3Ti layers are found to cover about 50% (linear scale) of the SiC surface. At the left side of Fig. 5, the plate-shaped layers (which are indicated by arrows) are observed to form on the SiC surface. These plate-shaped layers are found to be the ternary Ti_3SiC_2 and binary Al_4C_3 compounds, which have dark and bright contrasts in the micrograph, respectively. Note that a volume fraction of the Al_4C_3 layers is smaller than that of the Ti_3SiC_2 layers, which consist with the XRD results of Fig. 4. In the Ge/Ti/Al ohmic contacts, the Ti_3SiC_2 and Al_3Ti layers are found to directly contact to the SiC surface. Figures 6(a) and 6(b) show the SADPs obtained from the 4H–SiC substrate and the Ti_3SiC_2 layer, respectively. The incident electron beam is along the ⟨$\bar{2}$110⟩ direction of the 4H–SiC. By indexing the SADPs, the Ti_3SiC_2 layer was found to have an epitaxial orientation relationship with the 4H–SiC substrate,

$$(0001)_{TSC}//(0001)_S \text{ and } \langle\bar{2}110\rangle_{TSC}//\langle\bar{2}110\rangle_S$$

$$(\mathrm{TSC{:}Ti_3SiC_2, S{:}SiC}).$$

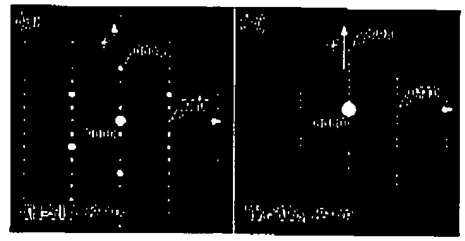

FIG. 6. Selected area diffraction patterns (SADPs) obtained from (a) the 4H–SiC substrate and (c) ternary Ti_3SiC_2 compound layer in the Ge/Ti/Al contact. (The incident electron beam is along the SiC⟨$\bar{2}$110⟩ zone axis.)

The result of the present SADP analysis is in good agreement with that of the XRD analysis of Fig. 4. Both the 4H–SiC ($P6_3/mc$; $a=0.307$ nm, $c=1.005$ nm)[21] and Ti_3SiC_2 ($P6_3/mmc$; $a=0.306$ nm, $c=1.763$ nm)[22] have the hexagonal unit-cell structure, and the lattice mismatch between the basal planes of Ti_3SiC_2 and 4H–SiC across the interface is approximately 0.4%. A cross-sectional high-resolution TEM micrograph of the Ti_3SiC_2 layer/SiC interface, which is taken along the SiC⟨$\bar{2}$110⟩ zone axis, is shown in Fig. 7. The (000*l*)-indexed lattice fringes are observed along the direction parallel to the interface in both the Ti_3SiC_2 layer and the SiC substrate. No contamination or amorphous oxide layers are observed at the interface, and thus, the Ti_3SiC_2 layer makes a direct contact on the SiC, as indicated by the arrows. The interface is found to be atomically flat with large (0001)-oriented terraces. The density of

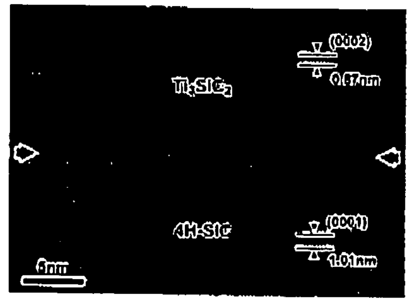

FIG. 7. Cross-sectional high-resolution TEM micrograph at the interface between the ternary Ti_3SiC_2 compound layer and the 4H–SiC. (The incident electron beam is along the SiC⟨$\bar{2}$110⟩ zone axis.)

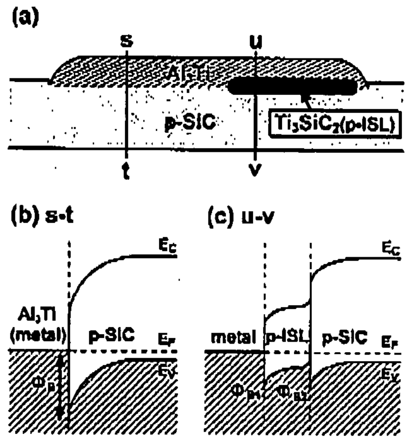

FIG. 8. Schematic illustrations of (a) cross-sectional microstructures of the Ge/Ti/Al contact and the predicted energy-band diagrams at (b) the Al_3Ti/SiC and (c) the Ti_3SiC_2/SiC interfaces through the *s-t* and *u-v* paths, respectively.

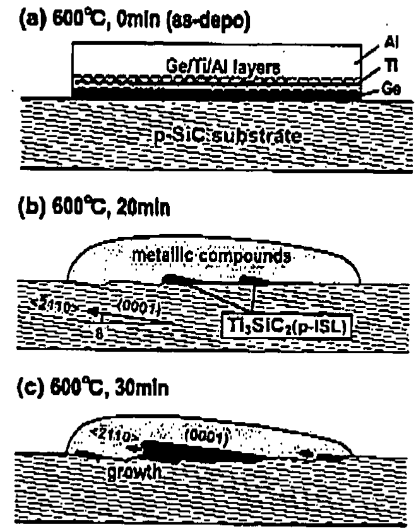

FIG. 9. Schematic illustrations of the cross-sectional microstructures of the Ge/Ti/Al contacts before and after annealing isothermally at 600 °C.

misfit dislocations at the interface is extremely low as calculated from the lattice mismatch between the Ti_3SiC_2 and the SiC. (Note that no misfit dislocation is observed in the present TEM micrograph.) The interfacial microstructures, which consisted of heteroepitaxial Ti_3SiC_2 layers after annealing, are common features in the TiAl-based ohmic contacts.

IV. DISCUSSION

A. Formation mechanism of Ge/Ti/Al ohmic contacts

A formation mechanism of the Ge/Ti/Al ohmic contacts is proposed based on the present XRD results of Fig. 4 and the TEM observation of Fig. 5. A cross section of the Ge/Ti/Al ohmic contact formed on the *p*-type SiC is shown schematically in Fig. 8(a). The Al_3Ti metallic compounds and the Ti_3SiC_2 layers contact directly to the SiC substrate. In the Ge/Ti/Al contacts, the electric current transport through the Al_3Ti/SiC and the Ti_3SiC_2/SiC interfaces as shown by paths *s-t* and *u-v*, respectively. The current transport mechanisms through these paths to the *p*-type SiC are different, and the predicted band diagrams through the *s-t* and *u-v* paths are shown in Figs. 8(b) and 8(c), respectively. A large Schottky barrier is formed at the interface between the Al_3T metallic compounds and *p*-type SiC. This large height barrier (Φ_B) interrupts the current transport through the contact metal/*p*-SiC interface, causing a large contact resistance at the interface. However, since the Ge/Ti/Al contacts provided an ohmic behavior after annealing at 600 °C for 30 min, the formation of the Ti_3SiC_2 compound layers must reduce the barrier height, as shown in Fig. 8(c). Tsukimoto *et al.*[17] reported in the Ti/Al and Ni/Ti/Al ohmic contacts that the formation of the Ti_3SiC_2 compound layers acted as an intermediate semiconductor layer (ISL) with a *p*-type conduction at the interface, which reduced the high barrier heights into two low barrier heights (Φ_{B1} and Φ_{B2}), as shown in Fig. 8(c). Therefore, the currents were believed to transport mainly across this interface with low barrier heights. In the present study, it was found that the formation mechanism of the Ge/Ti/Al contacts is similar to that observed previously in the Ti/Al and Ni/Ti/Al contacts, as reported by Tsukimoto *et al.*[17]

The results of the *I-V* characteristics (Fig. 1) and the microstructural analysis by XRD (Fig. 4) of the Ge/Ti/Al contacts after annealing also support the importance of the Ti_3SiC_2 formation to reduce the contact resistances. Cross-sectional microstructures of the Ge/Ti/Al contacts before and after annealing are illustrated schematically in Fig. 9. Schottky behavior is observed in the Ge/Ti/Al contact before annealing at 600 °C because no Ti_3SiC_2 compounds are formed, as shown in Fig. 9(a). After annealing at 600 °C for 20 min, the Ti_3SiC_2 layers are formed locally at the interface, as shown in Fig. 9(b), and the electric current transports through the metal/Ti_3SiC_2/SiC interfaces, although the volume fraction of the Ti_3SiC_2 layers is small. Residual Al and metallic compounds, such as Al_3Ti, cover primarily the SiC surface, as shown in Fig. 9(b), and thus, the specific contact resistance is extremely large. Further growth of the Ti_3SiC_2 layers at the interface after annealing for 30 min resulted in a reduction of the contact resistance, as shown in 9(c). The coverage of the Ti_3SiC_2 layers on the SiC surface is believed to influence strongly on the specific contact resistance of the Ge/Ti/Al contacts. In order to reduce further the contact resistances of the Ge/Ti/Al contacts, both the increase of the coverage and the reduction of the Ti_3SiC_2 layer thickness by optimizing the contacting metal thicknesses and the annealing conditions are needed.

B. Comparison among the TiAl-based ohmic contacts

The contact properties of the Ge/Ti/Al contacts[18] investigated in this study were compared with those of the conventional Ti/Al[9,12,17] and Ni/Ti/Al ohmic contacts,[16,17] and the results are summarized in Table II. Although the

TABLE II. Contact properties and microstructures of TiAl-based ohmic contacts.

TiAl-based contact	Ti/Al (Refs. 9, 12, and 17)	Ni/Ti/Al (Refs. 16 and 17)	Ge/Ti/Al (Ref. 18)
Annealing temperature (°C)	1000	800	600
Contact resistance (Ω cm^2)	1×10^{-6}	7×10^{-5}	1×10^{-4}
(Dopant concentration)	($N_A=1.2\times10^{19}$ cm^{-3})	($N_A=3.0\sim4.5\times10^{18}$ cm^{-3})	($N_A=4.5\times10^{18}$ cm^{-3})
Surface roughness (μm)	4.4	0.8	~1.0
Thermal stability	500 °C, 2 h	400 °C, 10 h	400 °C, 10 h
Reaction depth	Deep	Shallow	Shallow
Interfacial carbide	Ti_3SiC_2	Ti_3SiC_2, Al_4C_3	Ti_3SiC_2, Al_4C_3

Ge/Ti/Al contacts have the excellent contact properties, such as low-temperature formation, smooth surface morphology, high thermal stability, and shallow reaction depth into the SiC substrates, these contacts yield higher contact resistance to the p-type SiC compared with the other TiAl-based contacts. As discussed earlier, the ternary Ti_3SiC_2 layers are essential to cover most of the SiC surface to prepare the low-resistance TiAl-based ohmic contacts. Therefore, the investigation should be continued to find a fabrication process to increase the Ti_3SiC_2 layer coverage on the SiC surface for the Ge/Ti/Al contacts.

V. SUMMARY

In order to understand an ohmic contact formation mechanism of the Ge/Ti/Al ohmic contacts with specific contact resistances of approximately 1×10^{-4} after annealing at 600 °C, the electrical properties and the microstructures were investigated by the I-V measurements, XRD analysis, and TEM observations. The cross-sectional TEM observations revealed that the ternary Ti_3SiC_2 compound layers had directly contacted to the SiC substrate surface and the Ti_3SiC_2 layers had a hetero epitaxial relationship with the SiC substrates as follows:

$$(0001)\langle\overline{2}110\rangle_{TSC}//(0001)\langle\overline{2}110\rangle_{S}\ (\mathrm{TSC{:}Ti_3SiC_2,S{:}SiC}).$$

Comparison of the microstructures and the electrical properties of the Ge/Ti/Al ohmic contacts concluded that the reduction of the Schottky barrier height (at the contacting metal/p-SiC interfaces) was caused by the formation of the Ti_3SiC_2 layers, which acted as a p-type ISL at the metal/SiC interfaces. This formation mechanism of the Ge/Ti/Al contacts was found to be similar to that proposed in the Ti/Al and Ni/Ti/Al ohmic contacts. In order to further reduce the contact resistances, a fabrication process to increase the coverage of the Ti_3SiC_2 layers on the SiC surface by optimizing the contact metal thickness and the annealing conditions should be developed.

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